

[0052] Thus, the overall effect of the operation of the protection circuit 110 is that it exhibits a dynamic trip threshold, which is set as an inverse function of the current I with an offset value. The integrations and the trip constant are moved to the front ends of the protection circuit 110, and both are functions of the load current I. This transposition simplifies the analog circuit of the protection circuit 110 by eliminating the need to square the current I, and forgoing the added cost, complexity, size, and power consumption of a multiplier.

[0053] The output voltage V_{th1} of the first current integrator 112 can be expressed, as a function of time, through Equation 3:

$$V_{th1}(t) = V_{Curr}(1 - e^{-t/R_1C_1}) \quad \text{Equation 3}$$

[0054] In some embodiments, the value of the second through eighth resistors R_2 - R_8 may be set as follows:

[0055] $R_2 = R_5 = R_{f1}$

[0056] $R_3 = R_4 = R_{f1}$

[0057] $R_7 = R_{f2}$

[0058] $R_8 = R_{f2}$

[0059] In such embodiments, the threshold voltage V_{th2} generated by the summing amplifier 116 (e.g., the second operational amplifier 126) may be expressed, as a function of time, through Equation 4:

$$V_{th2}(t) = V_{Offset} - \left(\frac{R_{f1}R_{f2}}{R_{i1}R_{i2}} \right) V_{Curr} \left(1 - e^{-t / \left(\frac{R_{i1}R_{f1}C_2}{R_{i1} + R_{f1}} \right)} \right) \quad \text{Equation 4}$$

[0060] When the first and second inputs of comparator 118 become equal (i.e., when $V_{th1} = V_{th2}(t)$), the comparator 118 is triggered and generates the trip signal S_{Trip} . When V_{Curr} is zero, V_{th2} is equal to V_{Offset} . The following Equation 5 is arranged to solve for the input voltage V_{Curr} as a function of time:

$$V_{Curr}(t_{Trip}) = \frac{V_{Offset}}{(1 - e^{-t_{Trip}/R_1C_1}) + \left(\frac{R_{f1}R_{f2}}{R_{i1}R_{i2}} \right) \left(1 - e^{-t_{Trip} / \left(\frac{R_{i1}R_{f1}C_2}{R_{i1} + R_{f1}} \right)} \right)} \quad \text{Equation 5}$$

[0061] where t_{Trip} represents the trip time of the protection circuit 110 for a given input voltage $V_{Curr}(t_{Trip})$, or, equivalently, for a given load current I. Plotting the load current I as a function of trip time t_{Trip} yields an I²t trip curve that approximates that of FIG. 1, given appropriate selection of the values R_{i1} , R_{i2} , R_{f1} , R_{f2} , C_1 and C_2 . The offset voltage V_{Offset} is proportional to the trip threshold current $I_{threshold}$, which is determined according to a specific design application and is generally set above the rated current of the conductor 106. The offset voltage V_{Offset} is chosen such that the protection circuit 110 does not trip when the load current is less than the trip threshold current $I_{threshold}$. According to some embodiments, the relationship between the offset voltage V_{Offset} and the trip threshold current $I_{threshold}$ is expressed as:

$$V_{I_{Threshold}} = V_{Offset} \times \frac{R_{i2}}{R_{i2} + R_{f2}} \quad \text{Equation 6}$$

[0062] where $V_{I_{Threshold}}$ represents a voltage output of a current sensor within the protection circuit 110 measuring a load current equal to the trip threshold current $I_{threshold}$. Equation 6 may be derived by setting V_{th1} equal to V_{th2} (of Equations 3 and 4) after a long period of time has passed (e.g., at time infinity), when C_1 and C_2 are fully charged and settled.

[0063] FIG. 5 is a diagram 140 comparing the ideal I²t trip characteristic with that of the approximated I²t trip characteristic of the protection circuit 110 according to some exemplary embodiments of the invention.

[0064] Referring to FIG. 5, the curve 150, which represents the approximate I²t trip characteristic of the protection circuit 110 as defined by Equation 5, closely follows the curve 10, which represents an ideal I²t trip characteristic as simulated through software. For example, the R-squared calculated value (i.e., the coefficient of determination) between the curves 10 and 150 may be about 0.9996 or higher.

[0065] As is shown by Equation 5, the curve 150 may be shifted along the Y-axis of diagram 140, which represents the percentage of rated current, and along the X-axis of diagram 140, which represents time, by adjusting the values of the R_{i1} , R_{i2} , R_{f2} , C_1 , C_2 and V_{Offset} values. For example, the values V_{Offset} , R_{i2} and R_{f2} may be used to set the trip threshold current $I_{threshold}$, moving the curve 150 along the Y-axis. Further, the values R_{i1} , R_{i2} , C_1 , and C_2 are used to set the characteristic (e.g., shape) of the curve profile along the X-axis.

[0066] While the protection circuit 110 generates an I²t trip characteristic shown by curve 150, the flat region 160 of diagram 140 may be a result of a control signal from a controller (not shown in FIG. 4), which signals the switch 108 (see FIG. 2) to deactivate when the current I exceeds a preset limit (e.g., is 10 times the nominal current rating of the conductor 106).

[0067] As will be understood by a person of ordinary skill in the art, in the description above, the first and second operational amplifiers 124, 126 exhibit high gain and operate in their respective linear regions.

[0068] The protection circuit 110 according to embodiments of the invention utilizes an analog circuit for providing a close approximation of the I²t trip characteristic by integrating the conductor current with respect to time without squaring the current value. In so doing the protection circuit 110 according to embodiments of the invention avoids the use of multipliers, which can add to the size, complexity, power consumption, and cost of a device, and can reduce its reliability.

[0069] While this invention has been described in detail with particular references to illustrative embodiments thereof, the embodiments described herein are not intended to be exhaustive or to limit the scope of the invention to the exact forms disclosed. Persons skilled in the art and technology to which this invention pertains will appreciate that alterations and changes in the described structures and methods of assembly and operation can be practiced without